Voltage Impacts of a Variable Speed Wind Turbine on Distribution Networks

Seul-Ki Kim* and Eung-Sang Kim*

Abstract - The main purpose of this paper is to present a simulation model for assessing the impacts of a variable speed wind turbine (VSWT) on the distribution network and perform a simulation analysis of voltage profiles along the wind turbine installed feeder using the presented model. The modeled wind energy conversion system consists of a fixed pitch wind turbine, a synchronous generator, a rectifier and a voltage source inverter (VSI). Detailed study on the voltage impacts of a variable speed wind turbine is conducted in terms of steady state and dynamic behaviors. Various capacities and different modes of variable speed wind turbines are simulated and investigated. Case studies demonstrate how feeder voltages are influenced by capacity and control modes of wind turbines and changes in wind speed under different network conditions. Modeling and simulation analysis is based on PSCAD/EMTDC a software package.

Keywords: variable speed wind turbine, voltage profile, distribution feeder, real power control, reactive power control

1. Introduction

Wind power generation is attracting more attention from electric utilities and power consumers as an electric power supply alternative. Deregulation in electric power industry, increasing power demand, and economic, environmental, and political barriers to developing generation sources and reinforcing power delivery infrastructure place a great emphasis on making good use of wind energy in electric power system [1].

Wind energy conversion installations are manly being deployed on distribution systems. Viable spots for wind energy generation are mostly located in rural, coastal and mountainous areas where most of loads are served through radial distribution feeders. Since most distribution systems there have been designed to operate as radial systems and wind turbines hold an intermittent nature of their output constantly fluctuating or even them being tripped off owing to wind speed variations, wind turbine grid interface has the potential to degrade system reliability and result in power quality issues such as voltage variations, harmonics and flickers [2]. Deeper understanding of the interconnection issues is essential for interconnecting wind turbines to distribution power system.

This paper addresses the modeling of a variable speed wind turbine for steady state and dynamic simulation study and presents a simulation analysis of voltage impacts on the distribution feeder with a variable speed wind turbine. Wind energy conversion scheme using a VSI for grid interface is described.

Voltage impacts on feeder voltages resulting from operating a variable speed wind generation connected to distribution feeder are presented, using an example distribution feeder as a basis for analysis. Bus voltage fluctuations along the feeder are compared with changing the size of a wind turbine added to the distribution feeder and the control mode of the wind turbine power inverter, i.e. voltage regulation mode or constant power factor mode. Worst case study is carried out to determine the allowable capacity limit in terms of steady state voltage analysis. Dynamic analysis of voltage response to wind power output fluctuations due to drastic changes in wind speed and control modes of a wind turbine is made, looking into how the WT works under different control modes and how feeder voltages respond to the output of the wind generation.

The PSCAD/EMTDC software is used for the modeling and computer simulations in this analysis [3].

2. A Variable Speed Wind Turbine

Basically two types of wind energy conversion schemes are used, constant speed and variable speed [4]. Fixed speed generators are most commonly deployed and directly connected induction machines. These machines are usually equipped with switched capacitor banks to compensate for the reactive power drawn by the induction machine.

Variable speed operation yields 20 to 30 percent more energy than the fixed speed operation, providing benefits in

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reducing power fluctuations and improving var supply. Falling prices of the power electronics have made the variable speed technology more economical [5].

2.1 VSWT Configuration

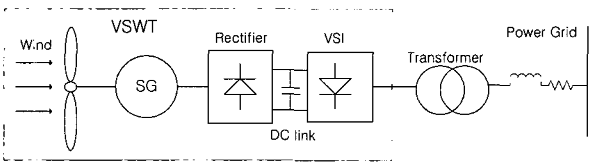


Fig. 1 the studied VSWT

The wind turbine used in this analysis is a variable speed wind turbine, which is typically connected to a distribution feeder through a voltage source inverter. Fig. 1 shows the schematic diagram of the studied wind energy conversion system. The system consists of a fixed pitch wind turbine, a high pole number modular PM synchronous generator [6], a rectifier module and a controllable IGBT voltage source inverter. The modeling of these elements and this wind energy conversion scheme is discussed below

2.2 Wind Turbine

A wind turbine converts wind energy into mechanical energy that is to be transferred into a wind generator via the wind turbine shaft. The mechanical power extracted by the wind turbine is, as shown in (1), a function of the wind speed available and the power curve of the machine depending on the type and operation condition of the wind turbine.

$$P_M = \frac{1}{2}\rho A C_P V_{WIND}{}^3 \qquad (1)$$

Where ρ (kg/m^3) is the air density, A (m^2) is the area swept out by the wind turbine blades and V_{WIND} (m/s) is the wind speed. C_P is the power coefficient representing the rotor efficiency and can be given as practical data of the performance test of the wind turbine by the manufacturer. C_P may be expressed as a function of the tip speed ratio (TSR) λ given by (2).

$$\lambda = \frac{\omega R}{V_{WIND}} \qquad (2)$$

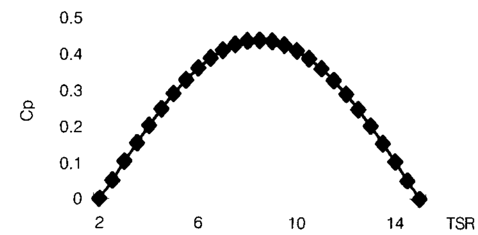


Fig. 2 C_P - λ curve

Where R (m) is the radius of the wind turbine rotor and ω (rad/s) is the rotor angular speed. Fig. 2 shows a typical power curve used in this study [7].

2.3 Controllable VSI

The Generator and rectifier system is uncontrolled and so control has to be implemented by the power electronics inverter. Current-controlled VSIs can generate an ac current which follows a desired reference waveform so can transfer the captured real power along with controllable reactive power [2]. Several types of power electronics interface have been investigated. Control concept in this study is based on DQ control scheme shown in Fig. 3. DQ control uses dq-axis transform to decouple real and reactive components and enables real power and reactive power to be separately controlled by specifying the respective reference values of P_{REF} and Q_{REF} for the both power outputs and independently adjusting the magnitude of the D-axis current I_D and that of the Q-axis current I_Q [8]. The inverter firing signals are generated by the sine pulse width modulation (SPWM) technique, where the desired current vector $\boldsymbol{I_{ABC\_REF}}$ and actual current vector $\boldsymbol{I_{ABC}}$ are compared and the error signal vector is compared with a triangle waveform vector to generate the inverter firing signals. The reference values P_{REF} and Q_{REF} of a wind turbine are dependent on what VSI's control strategies are taken for real and reactive power outputs, and specification of the values will be addressed in the following sections.

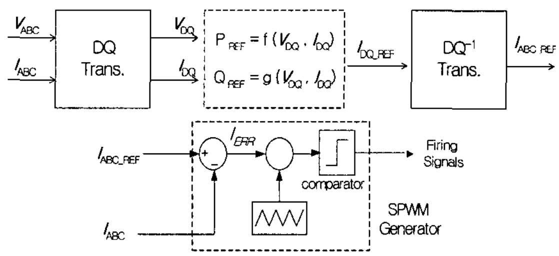


Fig. 3 DQ control of VSI

2.4 Variable Speed Operation Control

The most outstanding advantage of the variable speed operation over the fixed speed operation in extracting energy from wind is that the variable speed system is able to extract the maximum energy from varying wind speed [5]. For a given wind speed, the rotor efficiency C_P varies with TSR, as shown in Fig. 2. This indicates the C_P varies with the rotor angular speed ω. The maximum value of C_P occurs approximately at the same rotor speed that gives peak power in the power distribution curve of Fig. 4. The only operating mode for extracting the maximum energy is, therefore, to vary the turbine speed with varying wind speed such that at all times the TSR is continuously equal to that required for the maximum power coefficient C_P.

The maximum power extracted P_M^{max} from a variable speed wind turbine for a given speed in Fig. 3 may be expressed as in (3) [9].

$$P_M^{max} = \frac{1}{2}\pi\rho R^5 \frac{C_P^{max}}{\lambda_{OPT}^3}\omega^3 \quad (3)$$

Where C_P^{max} is the maximum value of the power coefficient and λ_{OPT} is the λ where the C_P is maximum, i.e. $C_P^{max} = C_P(\lambda_{OPT})$. The current controlled VSI in Fig. 1 makes variable speed operation possible by specifying the reference output as shown in (3) and controlling the real power output of the studied VSWT.

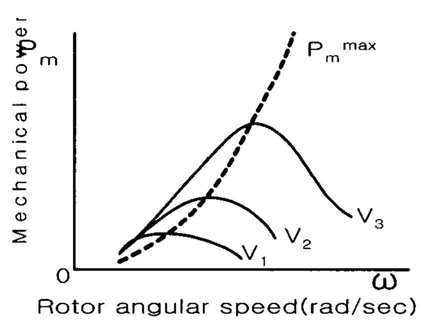


Fig. 4 Wind turbine power vs rotor speed

2.5 Reactive Power Control

Unlike asynchronous generators, synchronous generators have the ability to produce reactive power without the external var supply sources such as switched capacitors, and static var compensators [10]. A VSWT using a synchronous generator can operate as a reactive power generation source, independently of its real power production, with the aid of a controllable voltage source inverter. Various control modes can be used for determining the amount of compensation to provide. Possible control modes include power factor, kvar, current and voltage. Constant power factor mode and voltage regulation mode are used in this analysis.

In constant power factor control (PFC) mode, the reference value of the reactive power output Q_{REF} of the VSWT may be specified as the following equation (4).

$$Q_{REF} = P_{REF} \cdot \frac{\sqrt{1-PF^2}}{PF} \quad (4)$$

Where PF is power factor and P_{REF} is the reference value of the real power output of the VSWT.

In voltage compensation (VC) mode, the reactive power compensation is controlled in such a manner the voltage magnitude of the VSWT-connected bus at a specified level. The reference magnitude of the voltage to be regulated must be set between the acceptable limits for service voltages provided by the utilities.

The reactive capability limits of a VSWT are determined by MVA rating of the inverter, which may be described by.

$$Q_{LIMITS} = \pm\sqrt{S_{INV}^2 - P_{INV}^2} \quad (5)$$

Where Q_{LIMITS}, P_{INV} and S_{INV} are the reactive power limits, the real power output and MVA rating of the inverter, respectively.

3. Voltage Issues on VSWT

Voltage issues on the interconnection of variable speed wind generation into distribution systems may be divided into two categories, short-term (less than one minute) and long-term fluctuations (greater than one minute).

3.1 Short-term Impacts

Short-term impacts on voltage magnitude result from real and reactive power fluctuations produced by the wind turbine. The voltage variation levels on the distribution feeder are dependent on the size of the wind turbine connected and the configuration of the distribution system.

Power fluctuations of the wind turbine can be caused during continuous operation, including variations in wind speed, wind gusts, tower shadow effect and blade pitching, and switching operations such as cut-in and cut-out of wind turbine).

The power fluctuations resulting from wind speed variations can actually be smoothed due to the large mechanical inertia of the wind turbine and generator. The tower shadow effect that the wind speed on a blade is reduced as it passes the tower can introduce power fluctuations. However, since variable speed turbines can compensate for torque variations, only fixed speed types are susceptible to the phenomena [11]. For blade pitching the VSWT in this study is a fixed pitch type and the effect can be neglected as well. Accordingly, wind gust, and cut-in and cut-out operations of the wind turbine are the main factors which have considerable impacts on the feeder voltages in the short term analysis. The dynamic simulation analysis of these short-term variations will be made in the following chapter.

3.2 Long-Term Impacts

Long-term impacts on voltage variations are the change in average voltage on the feeder under the long-term conditions for the distribution system configuration, the system loading state, the size and output of the wind turbine and control mode of the VSWT. At the preliminary phase of planning wind turbine interface and determining the size and location of the wind turbine, these long-term variations must be exhaustively investigated. Also, the steady-state analysis of the long-term impacts will be described in the following

4. Voltage Impact Analysis

The distribution system into which a variable speed wind turbine is assumed being considered for integration is shown in fig. 5. Some system simplifications were made in the system to provide more generalized results.

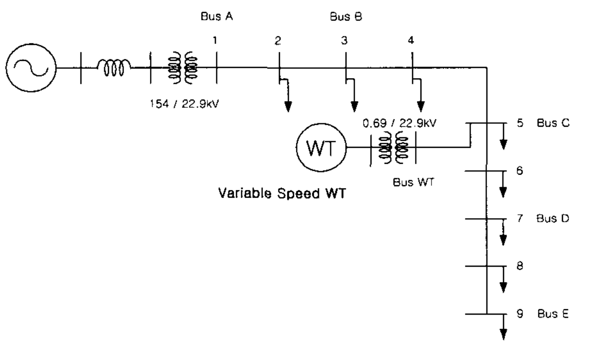


Fig. 5 One-line diagram of distribution system with VSWT

The point of common coupling for the WT is located at Bus WT approximately 10km from the utility substation. The length of each branch between neighboring two nodes is all the same 2km. It is assumed that every node but node 1 has the same amount of real and reactive load with the lagging power factor of 0.9. The substation transformer has a tap ratio 154/22.9kV with 45MVA rating and its secondary busbar voltage is adjustable at a value between allowable levels. ACSR 160mm^2 cable is considered for the 22.kV distribution feeder and its equivalent impedance is 0.182+j0.391 [Ω/km]. The maximum thermal rating of the feeder is 10

The wind turbine used in the analysis is a VSI-controlled and synchronous-machine-type VSWT. Five ratings of 1, 2, 3, 4 and 5 MVA are implemented for simulating size effects. The reactive capability limits of the wind turbine are calculated by (6). Two types of control mode, power factor control (PFC) and voltage compensation (VC), which are commonly used, are considered for comparison study. In case of PFC mode the control target is a typical value of 0.98 and the target value of the voltage magnitude for VC mode is set to 1.00 pu.

Simulations and analysis are performed using PSCAD/EMTDC program that has been widely used in modeling and simulation works by power engineers and researchers to analyze characteristics and operations of power system and apparatus.

4.1 Steady-state Analysis

The secondary winding of the substation transformer has taps that are adjusted according to the amount of the feeder loading. For the cases presented in this section, the winding tap is set as follows: (i) during off-peak load – 1.0 pu and (ii) during peak load – 1.036 pu.

Fig. 6 shows the voltage profiles across the 3MVA VSWT-installed feeder in case of possible combinations of load pattern (full load and no load), the WT output (maximum and zero) and the control modes, PFC mode (pf = 0.98) and VC mode (V_{REF} = 1.0 pu). The solid lines and the dotted lines represent cases with full load and cases with no load, respectively. The symbols of X and + indicate applications of WT with PFC mode and VC mode. The lines marked with a symbol of Rectangle are for cases with no WT. Fig. 6 illustrates that Output of the WT with PFC mode raises a voltage to high levels at all nodes for both cases of full load and no load. A more serious voltage rise condition may occur in a worse case during peak load time where the substation transformer secondary winding is tapped up to mitigate greater voltage drops on the feeder and the feeder loading suddenly gets reduced to minimum level. This worst case will be considered later on. VC control mode shows quite a different result from PFC mode. The voltage compensation control keeps the voltages almost unchanged or even lower compared to the cases with no WT. The different results between PFC and VC modes occur just because reactive power of the wind generation is supplied into the feeder in the constant power factor control and controlled for the terminal voltage to be kept constant in the voltage regulation strategy. Table 1 shows a comparison of voltage fluctuation percentages between a WT with PFC mode, a WT with VC mode and no WT applied. The power factor control results

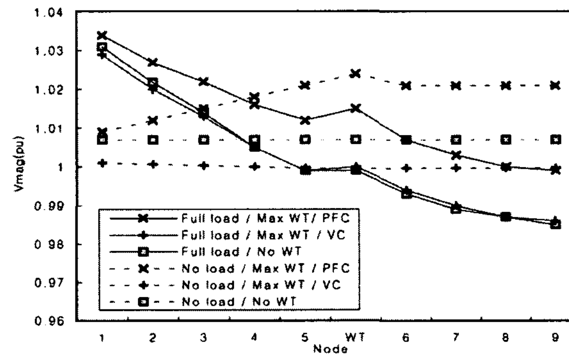


Fig. 6 Voltage profiles along feeder for Load, WT output and WT control mode combinations

in greater fluctuations than the voltage regulation mode with the exception of the voltage at node 1 and 2. It should be noted that whether the control mode is PFC or VC feeder operation with WT leads to a bigger level of voltage fluctuation spread.

Table 1 Voltage fluctuation percentage [%] for different WT controls

Node	1	2	3	4	5	WT	6	7	8	9
PFC	2.7	2	1.5	1.3	2.2	2.5	2.8	3.2	3.4	3.6
VC	3	2.1	1.1	0.7	0.8	0.8	1.4	1.9	2	2.2
no WT	2.4	1.5	0.7	0.2	0.8	0.8	1.4	1.8	2	2.2

For the case of full load feeder and PFC controlled WT in Fig. 6, WTs at full power with various capacities of 1, 2, 3, 4 and 5 MVA were simulated to see the size influence on the steady-state voltage profile. It is shown in fig. 7 that operating greater capacity results in a more spread voltage profile. Voltage spread at nodes before the WT node tends to grow bigger as a node is more distant from the substation, and after the node of the wind generation voltage profiles at nodes 6 to 9 show almost the same amount of voltage spread.

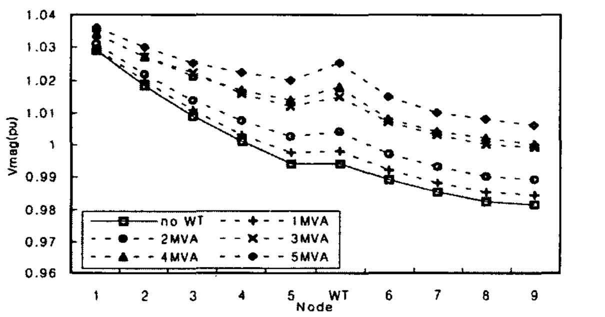


Fig. 7 Voltage profiles along feeder in case of various sizes of WT applied

The acceptable capacity of dispersed generation is usually established by deterministic methods, by taking a "worst scenario" of simultaneous maximum primary substation busbar voltage, maximum consumer loading and maximum generator output. If voltage turned out to be higher than an acceptable level, the output of the generator is reduced until the level is reached and this marks the limit of allowable installation capacity [12]. Certainly, such a worst-case determination method can be very severe and limiting for intermittent generators such as wind turbines, but, at the same time, may give information on the highly-reliable limit of interconnection capacity, which indicates how large capacity can be allowed to operate without violating an acceptable voltage limit even under the possible worst network condition, in terms of the steady-state voltage stability analysis.

Results of the worst-case analysis are shown in fig. 8 and fig. 9. The substation busbar voltage is 1.038 pu and the size of load at feeder is very light, 10% of maximum consumer loading. The variable speed WT is operating at approximately 90% of its full power. In such a worst condition, shown in fig. 8 is the voltage profile on the feeder for the VSWT of PFC control mode with maximum rating of 1 to 5MVA simulated. Applying capacity exceeding 2MVA results in violating the voltage limit 1.0455 pu and it can be said that 2MVA rating is the maximum allowable capacity limit based on the worst-case scenario analysis. If a VSWT with a rating of over 2MVA, say 3MVA, should be intended to be operating on this feeder, appropriate measures would have to be prepared against overvoltages occurring at node 4 to 9.

The overvoltage condition in the worst case can be alleviated by altering the control strategy of the wind turbine output into the voltage compensation mode. As shown in fig. 9, VC strategy provides a nearly flat and lower voltage profile for all the ratings implemented. Under VC mode the wind turbine monitors its terminal bus voltage, compares the actual value with the desired value, say 1.0 pu, and controls var exchange with the distribution feeder. Voltage at bus WT with no wind turbine is 1.034 pu, higher than the reference voltage, and the WT absorbs reactive power, within the reactive capability limit for applied MVA rating, from the feeder to keep the terminal voltage at the specified level.

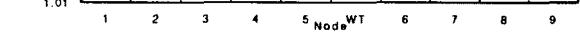


Fig. 8 Rise in voltage profile along feeder with WT of PFC mode under the worst-case scenario

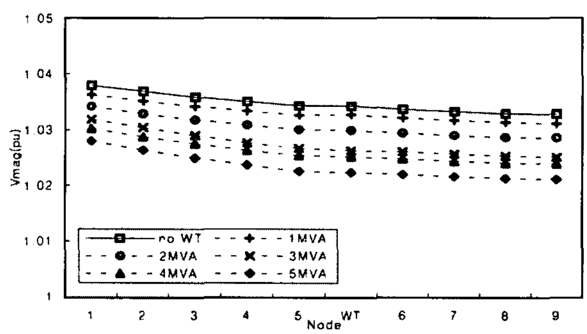


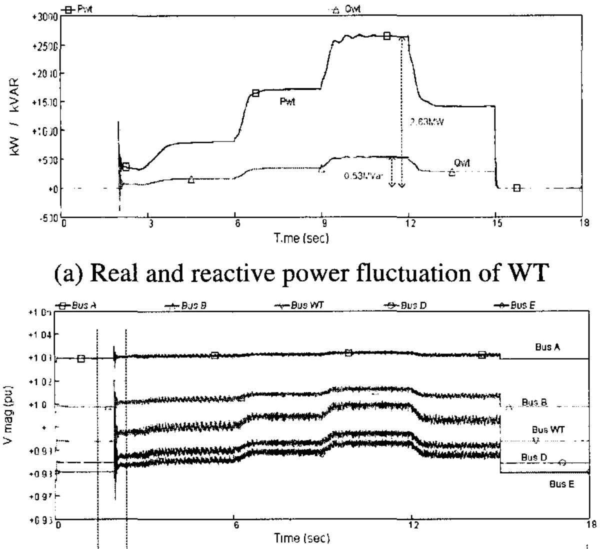
Fig. 9 Change in voltage profile along feeder with WT of VC mode under the worst-case scenario

4.2 Dynamic Analysis

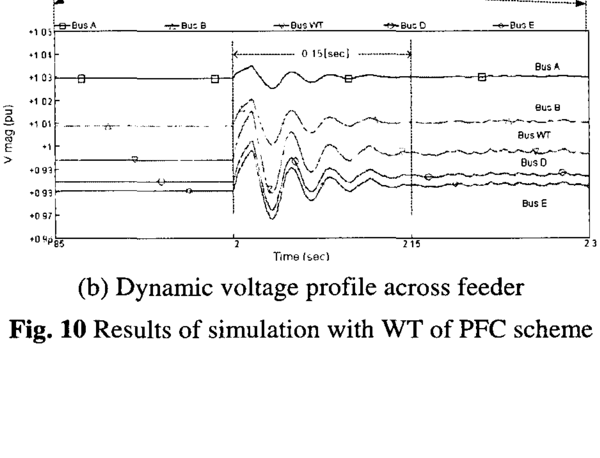
An intermittent nature of wind keeps the real and reactive output of wind turbines constantly fluctuating, even frequently cutting in and out them from the distribution network, and may give rise to a significant change in voltage profile along feeders. As described earlier, short-term voltage variations result from wind gust and switching operations of wind turbines (of course, cut-in and cut-out of WTs typically come from wind variations), for which Dynamic behaviors are simulated with the same network configuration as in fig. 5 and the following system states. A 3MVA variable speed wind turbine operating at full power is applied on the feeder at full load. The substation tap is set to 1.036 pu for heavy load condition. At the initial stage the wind turbine is not connected to the feeder because of lower wind speed below cut-in speed. At 2 sec. Wind speed starts to go over the cut-in speed and the wind turbine starts operating with the distribution feeder. Twice of wind gust occur at 6 and 9 [sec], and sudden consecutive drops in wind speed at 12 and 15 [sec]. The last wind change by which wind speed goes below cut-in speed again removes the wind turbine from the feeder.

In fig. 10, shown are real and reactive power output of the wind generation operating with the power factor control scheme under the wind condition as described above and dynamic voltage response to the changes in wind speed under PFC control of the WT. After the variable-speed wind generation starts operating it is supplying maximum real power corresponding to given wind condition and reactive power at power factor 0.98 into the distribution feeder, say 2.63MW and 0.53Mvar during the interval of 9 to 12 [sec], until the WT is cut out from the feeder, as shown in fig. 10 (a). Both active and reactive power injections into the feeder escalate the feeder voltage level. It should be noted in fig. 10 (b) that voltage profiles at the feeder buses show the nearly same patterns as changes in the WT power output. This trend explains well that the feeder voltages are closely related to and directly influenced by changes in wind speed. It can be observed that the farther from the substation and the closer to the WT bus a bus is on the feeder, the more distinct its voltage variation by wind gusts appears. The zoomed-in graph in fig. 10 (b) illustrates at the instant of the WT being connected voltage disturbance occurs, swings for about 0.15 [sec] and dies away. Due to this phenomenon by the cut-in operation of the wind turbine, some distortions and flickers may be experienced by sensitive load in use that is connected to this feeder.

Fig. 11 shows the results of simulating a WT in operation at VC mode. The wind generation produces maximum real power for given wind speeds into the feeder, same as

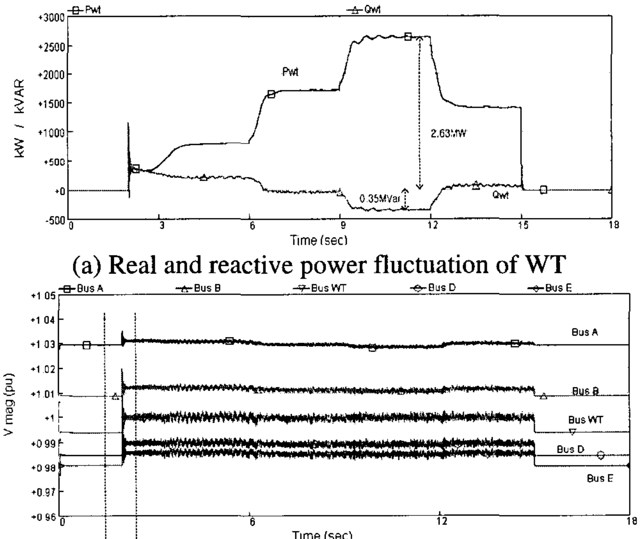


(a) Real and reactive power fluctuation of WT

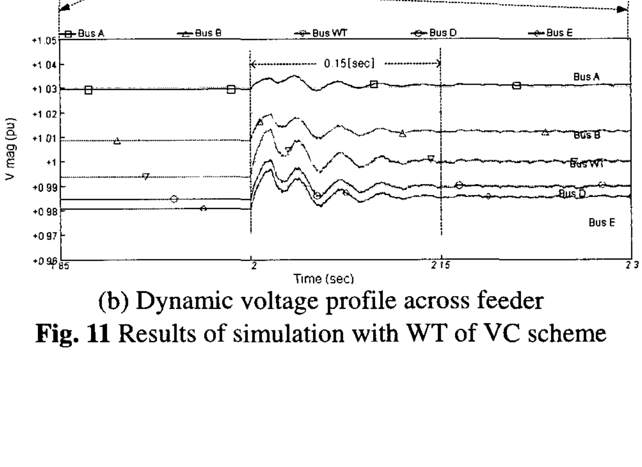


(b) Dynamic voltage profile across feeder

Fig. 10 Results of simulation with WT of PFC scheme



(a) Real and reactive power fluctuation of WT



(b) Dynamic voltage profile across feeder

Fig. 11 Results of simulation with WT of VC scheme the case of PFC mode in fig. 10 (a), but it generates (at intervals of 2 to 6.5 [sec] and 12.5 to 15 [sec]) or consumes (at 9 to 12.5 [sec]) a certain amount of reactive power to maintain bus WT voltage at the value of 1.0 pu in fig. 11 (a). This different injection type makes a significant difference from the previous case in a variation pattern of the feeder voltage with application of a variable speed wind turbine. As can be seen in fig. 11 (b), voltage at bus WT is kept constant and the feeder voltage profiles except at bus A are close to flat as long as the wind turbine is connected and in operation. Note that unlike the previous case, since the substation busbar is only source for reactive power on the feeder during the period between 9 and 12.5 [sec], the voltage at bus A is considered as relatively more influenced than voltages at other buses by the variations in reactive output of the WT, which originally come from wind speed changes. The shape of voltage profile at a bus closer to bus WT becomes closer to a perfect flat line. Voltage swings are also observed at the instant when the variable speed wind generation is added to the feeder in a close-up of the feeder voltage graph.

Table 2 shows relative voltage changes for 18 seconds simulated in the previous two cases. It is shown that a variable speed wind turbine with PFC strategy results in greater voltage fluctuations than that with VC strategy under the same wind varying condition from the viewpoint of dynamic behavior.

Table 2 voltage fluctuations [pu] due to wind speed variations

Bus		A	B	WT	D	E
PFC	Max	1.0321	1.0168	1.0099	0.9976	0.9936
	Min	1.0292	1.0087	0.9938	0.9844	0.9804
	ΔV	0.29%	0.81%	1.61%	1.32%	1.32%
VC	Max	1.0295	1.0115	1.0003	0.9895	0.9855
	Min	1.0279	1.0087	0.9938	0.9844	0.9804
	ΔV	0.16%	0.28%	0.65%	0.51%	0.51%

5. Conclusion

Wind energy generation is one of the best solutions to electricity industry crisis that we are confronted with in respects of limited fossil fuel, environmental pollution, and economical and political barriers to reinforcing power system. For more promoted use of wind turbines into electric network, utilities and users should be provided with a simulation analysis tool and conduct comprehensive study on the impacts of adding wind turbines to power system.

In this paper, impacts of a variable speed wind turbine, which has been more and more used for its efficiency and controllability, on the feeder voltage have been studied in terms of steady state and dynamic analysis using a simulation model developed for this study. The modeling and simulation technique of a VSWT have been described.

The steady state analysis has shown feeder voltage fluctuations under various system conditions of feeder loading, substation bus voltage, and wind turbine output and control modes. Worst-case analysis was conducted to see the allowable capacity considering steady state voltage. Dynamic analysis results have revealed that under different control modes of the VSWT there are different patterns in voltage variations resulting from continuous and switching operations of the wind turbine. Voltage regulation strategy has shown better feeder voltage profiles in both analysis of steady state and dynamic behaviors.

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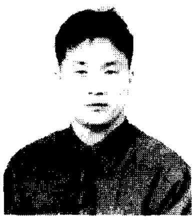

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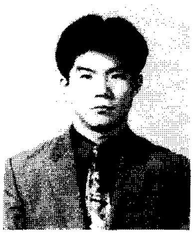

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